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Chapter 10

PROPERTIES OF FLUIDS

Objectives

- **Understand the basic concepts of fluid mechanics.**
- **Recognize the various types of fluid flow problems encountered in practice.**
- **Understand the vapor pressure and its role in the occurrence of cavitation (**it is the process of boiling in a **liquid** as a result of pressure reduction rather than heat addition).

Objectives

- Have a working knowledge of viscosity and the consequences of the frictional effects it causes in fluid flow.
- Calculate the capillary rises and drops due to the surface tension effects.

WHAT IS FLUID MECHANICS?

- **Fluid** – a substance that continually deforms (flows) under applied shear stress
- **Mechanics** – science concerned with behaviour of physical bodies when subjected to forces
- **Fluid Mechanics** – the science that deals with the behaviour of fluids at rest (fluid statics) or fluids in motion (fluid dynamics), and their subsequent effects on the surrounding environment

Application Areas of Fluid Mechanics

Natural flows and weather
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Boats
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Aircraft and spacecraft
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Power plants
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Human body
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Cars
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Wind turbines
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Piping and plumbing systems
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Industrial applications
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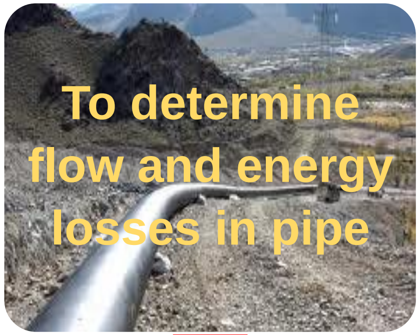
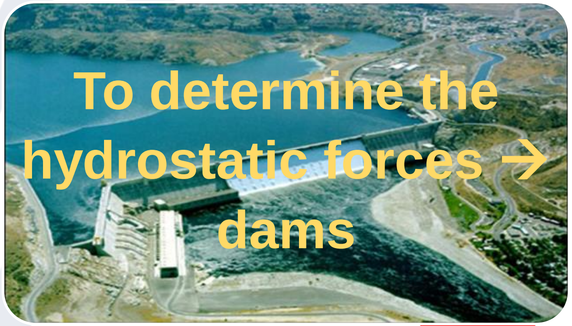
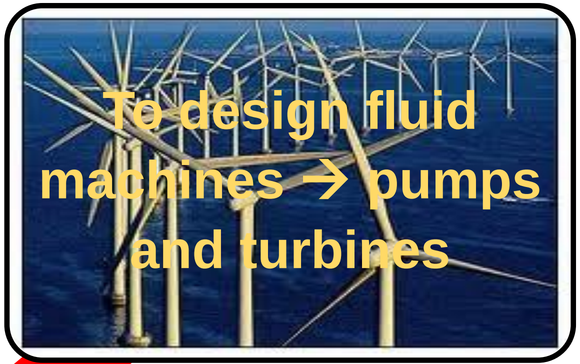
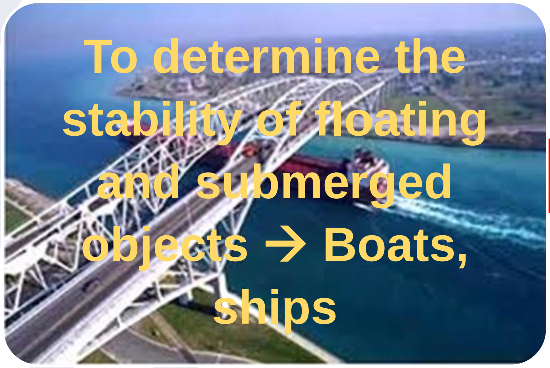
Important Of Fluid Mechanics

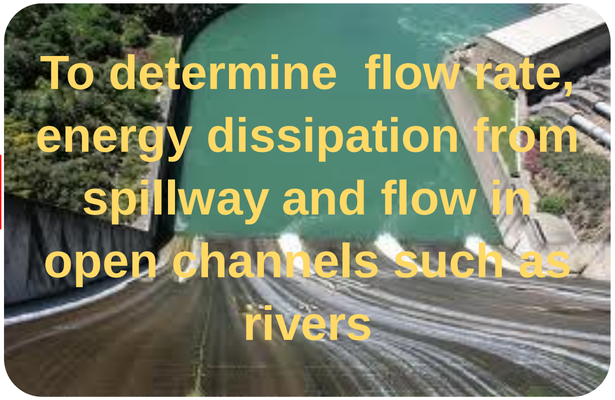




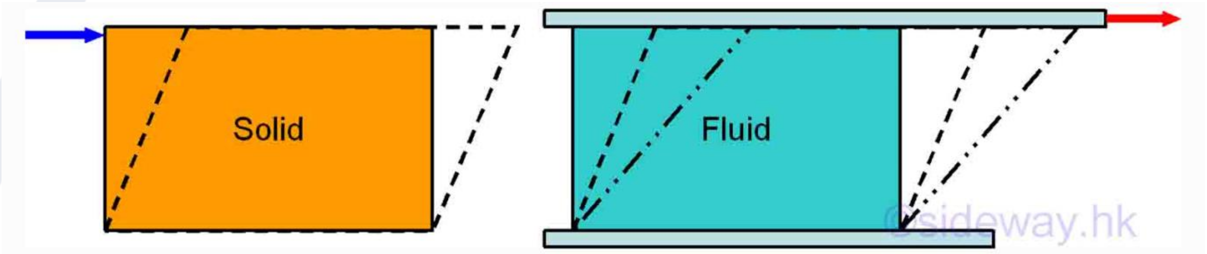


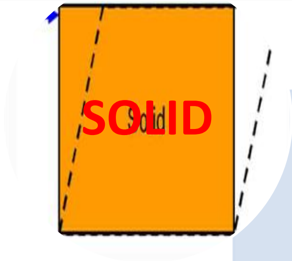
IMPORTANT OF FLUID MECHANICS TO ENGINEER





Difference Between Solid And Fluid





SOLID

- Have preferred shape
- Hard & not easily deformed
- Cannot deformed continuously under shear force

FLUID

- Does not have any preferred shape
- Soft & easily deformed
- Deformed continuously under shear force

Concept Of Fluid

In **FLUID:**

-The molecules can move freely but are constrained through a traction force called *cohesion*.

-This force is interchangeable from one molecule to another.

For **GASES:**

-It is very weak which enables the gas to disintegrate and move away from its container.

-A *gas* is a fluid that is easily compressed and expands to fill its container.

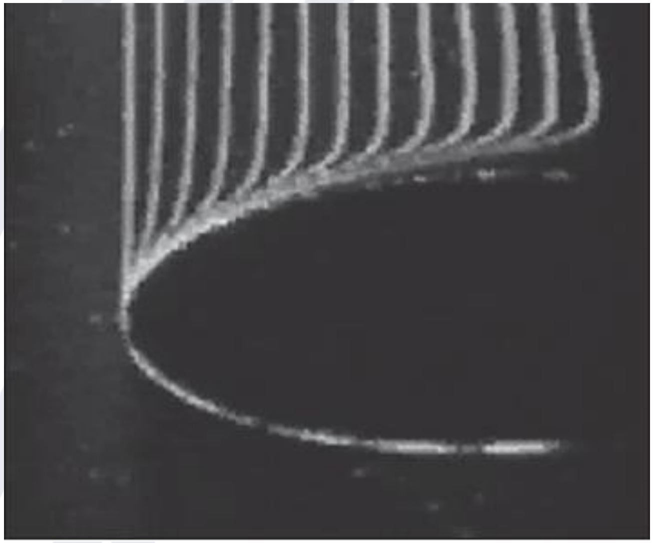
-It fills any vessel in which it is contained. There is thus no free surface.

For **LIQUIDS:**

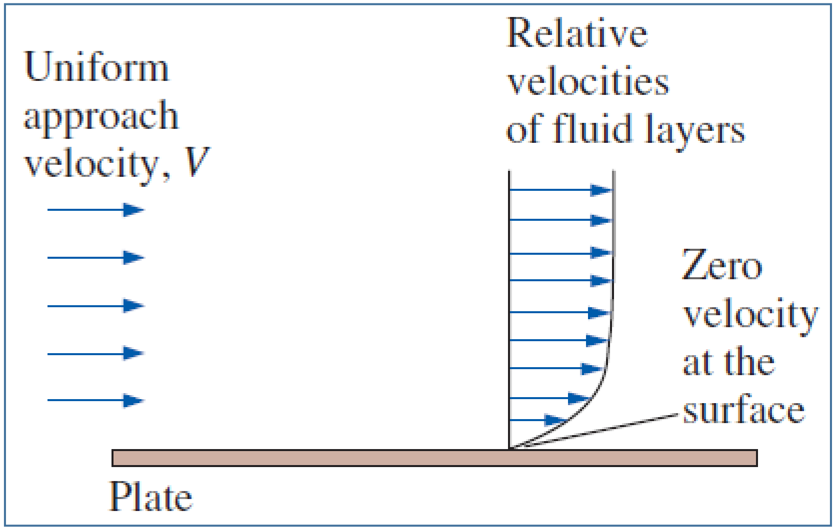
-It is stronger which is sufficient enough to hold the molecule together and can withstand high compression, which is suitable for application as hydraulic fluid such as oil.

-On the surface, the cohesion forms a resultant force directed into the liquid region and the combination of cohesion forces between adjacent molecules from a tensioned membrane known as *free surface*.

10-1 THE NO-SLIP CONDITION

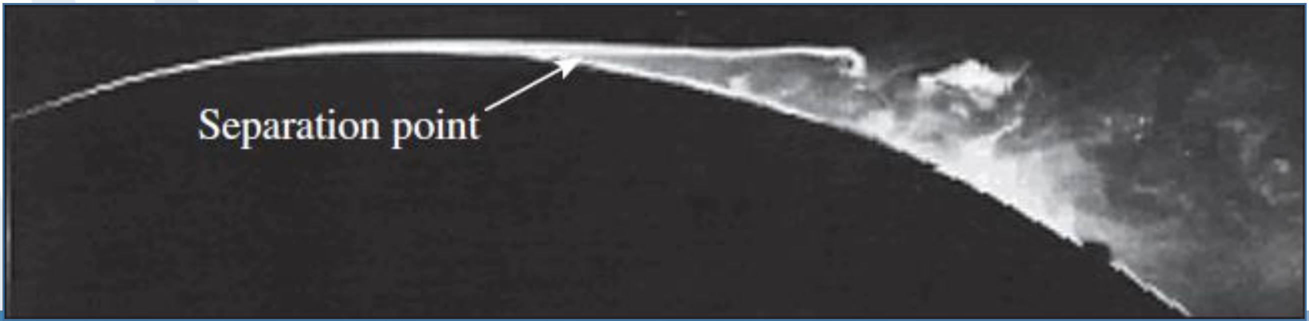


That is, a fluid in direct contact with a solid "sticks" to the surface, and there is no slip. This is known as the **no-slip condition.**



A fluid flowing over a stationary surface comes to a complete stop at the surface because of the no-slip condition.

The development of a velocity profile due to the no-slip condition as a fluid flows over a blunt nose.



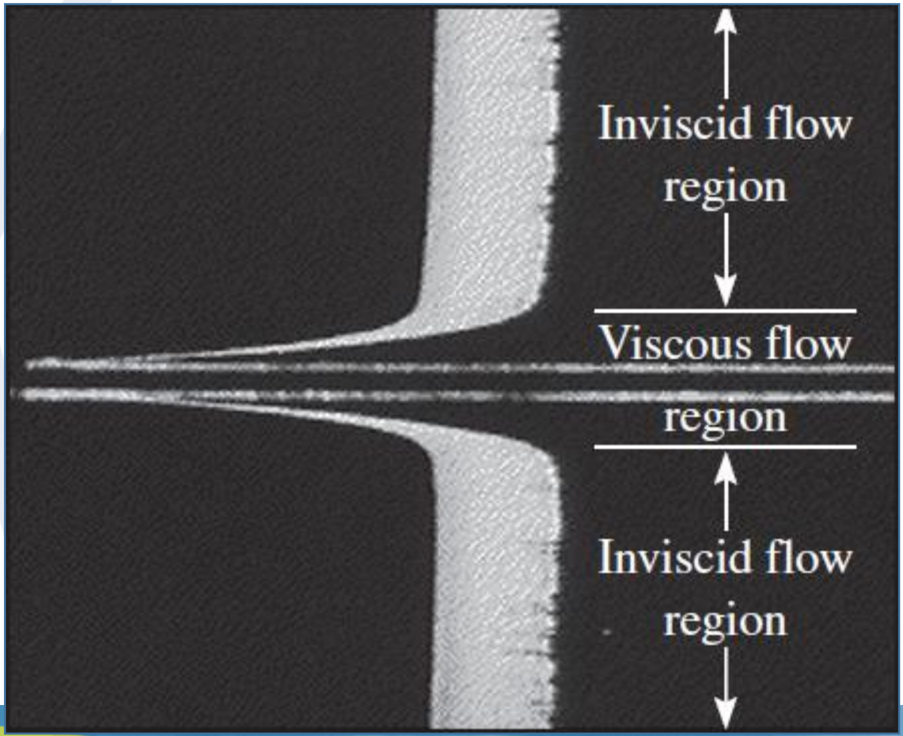
Flow separation during flow over a curved surface.

Boundary layer: The flow region adjacent to the wall in which the viscous effects (and thus the velocity gradients) are significant.

10-2 CLASSIFICATION OF FLUID FLOWS

Viscous flows: **Flows in which the frictional effects are significant.**

Inviscid flow regions: **In many flows of practical interest, there are *regions* (typically regions not close to solid surfaces) where viscous forces are negligibly small compared to inertial or pressure forces.**

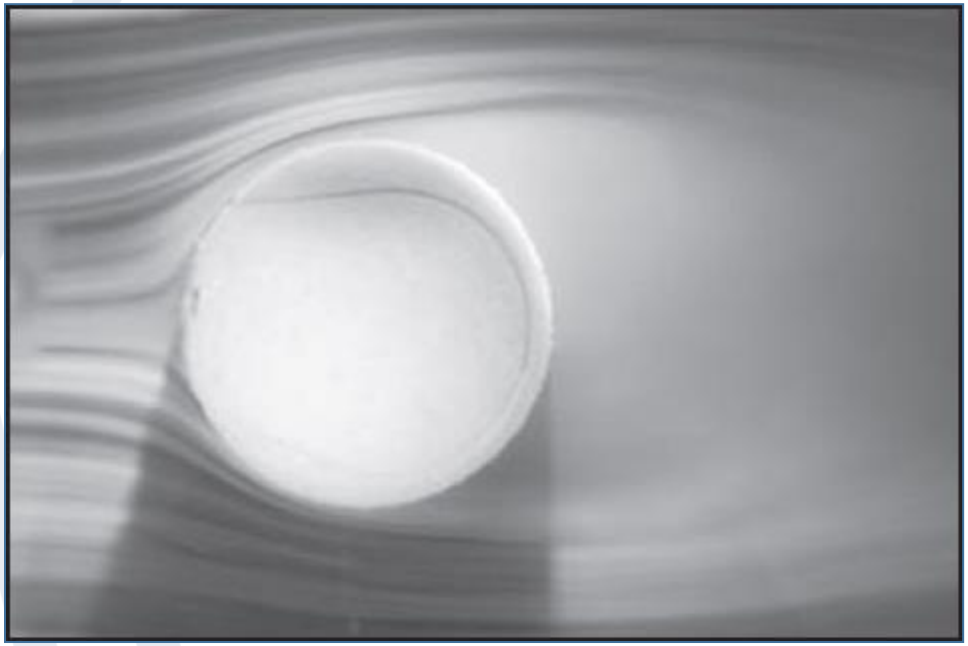


The flow of an originally uniform fluid stream over a flat plate, and the regions of viscous flow (next to the plate on both sides) and inviscid flow (away from the plate).

Internal versus External Flow

External flow: **The flow of an unbounded fluid over a surface such as a plate, a wire, or a pipe.**

Internal flow: **The flow in a pipe or duct if the fluid is completely bounded by solid surfaces.**



External flow over a tennis ball, and the turbulent wake region behind.

- **Water flow in a pipe is internal flow, and airflow over a ball is external flow .**
- **The flow of liquids in a duct is called *open-channel flow* if the duct is only partially filled with the liquid and there is a free surface.**

Compressible versus Incompressible Flow

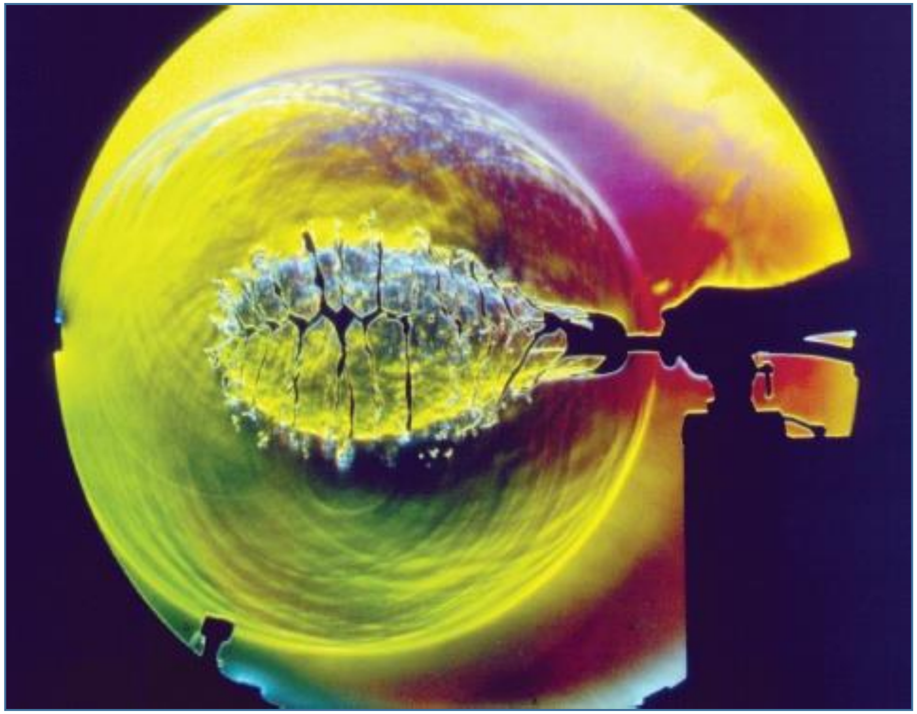
Incompressible flow: If the density of flowing fluid remains nearly constant throughout (e.g., liquid flow).

Compressible flow: If the density of fluid changes during flow (e.g., high-speed gas flow)

When analyzing rockets, spacecraft, and other systems that involve high-speed gas flows, the flow speed is often expressed by Mach number

$$\mathrm{Ma} = \frac{V}{c} = \frac{\text{Speed of flow}}{\text{Speed of sound}}$$

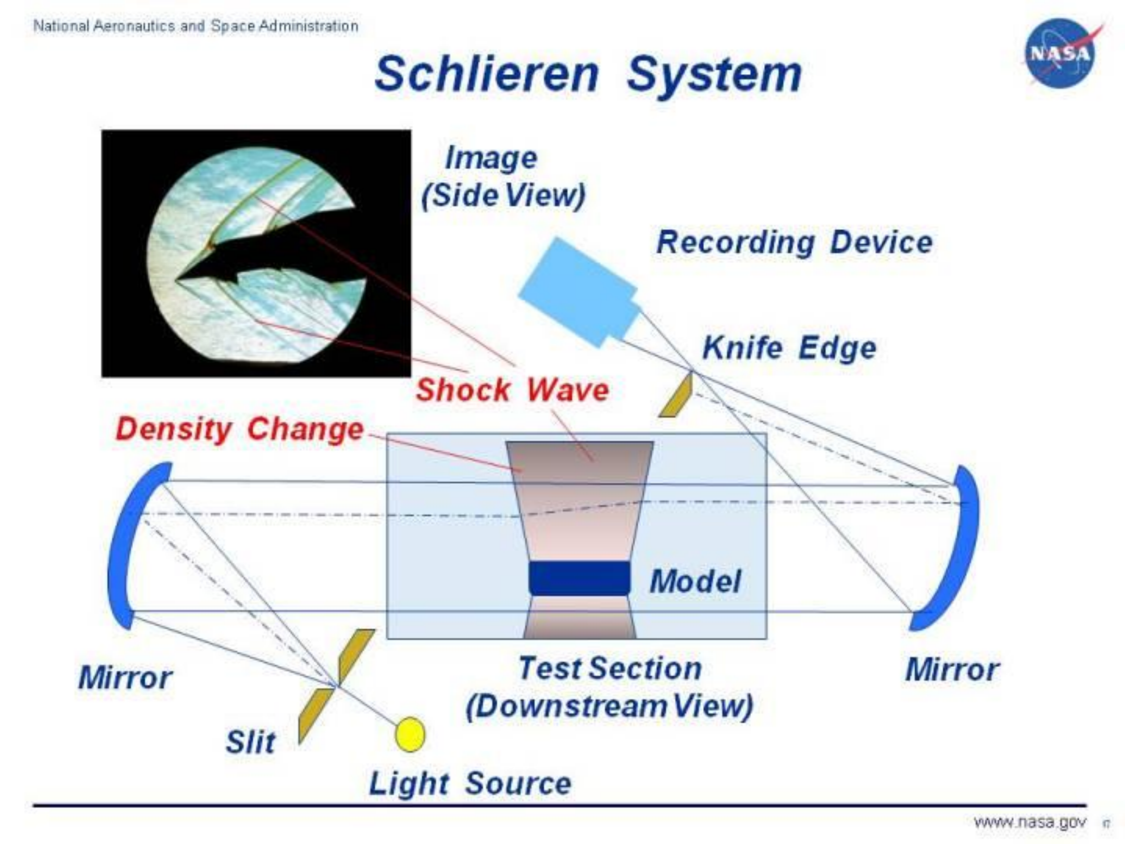
$\mathrm{Ma} = 1$ **Sonic flow**
$\mathrm{Ma} < 1$ **Subsonic flow**
$\mathrm{Ma} > 1$ **Supersonic flow**
$\mathrm{Ma} >> 1$ **Hypersonic flow**



Schlieren image of the spherical shock wave produced by a bursting balloon at the Penn State Gas Dynamics Lab. Several secondary shocks are seen in the air surrounding the balloon.

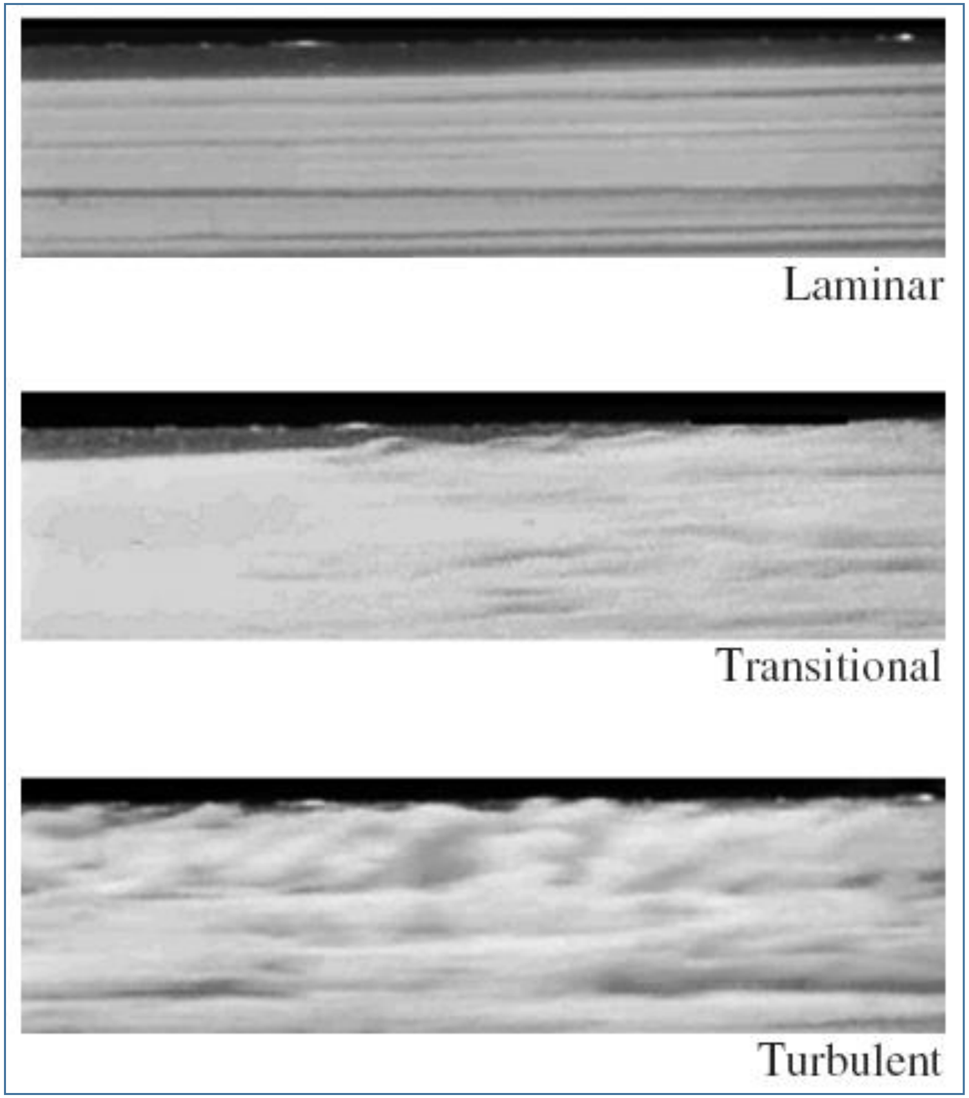
A **Schlieren** test is an optical **system** that detects changes within a test area medium (air) and records the changes in the form of an **image** on a screen.

The **image** is formed by refraction and scattering from what is introduced into the test area, which are areas of varying refractive index.



Laminar versus Turbulent Flow

- **Laminar flow:** The highly ordered fluid motion characterized by smooth layers of fluid. The flow of high-viscosity fluids such as oils at low velocities is typically laminar.
- **Turbulent flow:** The highly disordered fluid motion that typically occurs at high velocities and is characterized by velocity fluctuations. The flow of low-viscosity fluids such as air at high velocities is typically turbulent.
- **Transitional flow:** A flow that alternates between being laminar and turbulent.

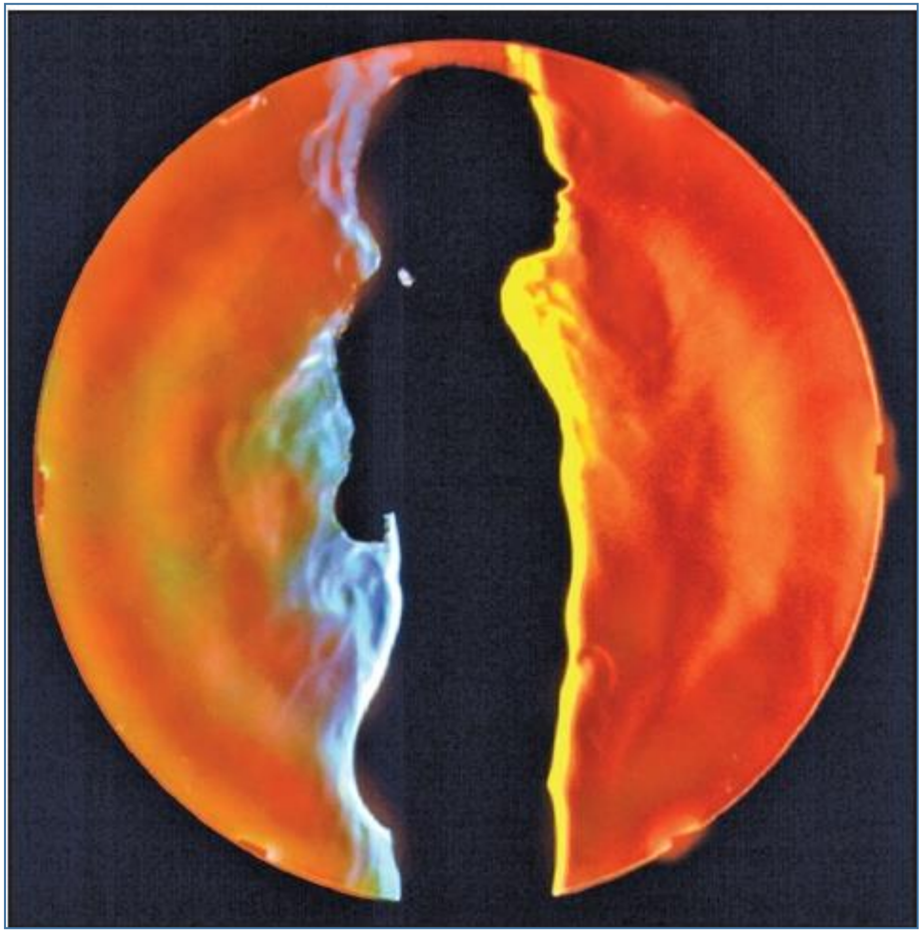


Laminar, transitional, and turbulent flows over a flat plate.

Natural (or Unforced) versus Forced Flow

Forced flow: A fluid is forced to flow over a surface or in a pipe by external means such as a pump or a fan.

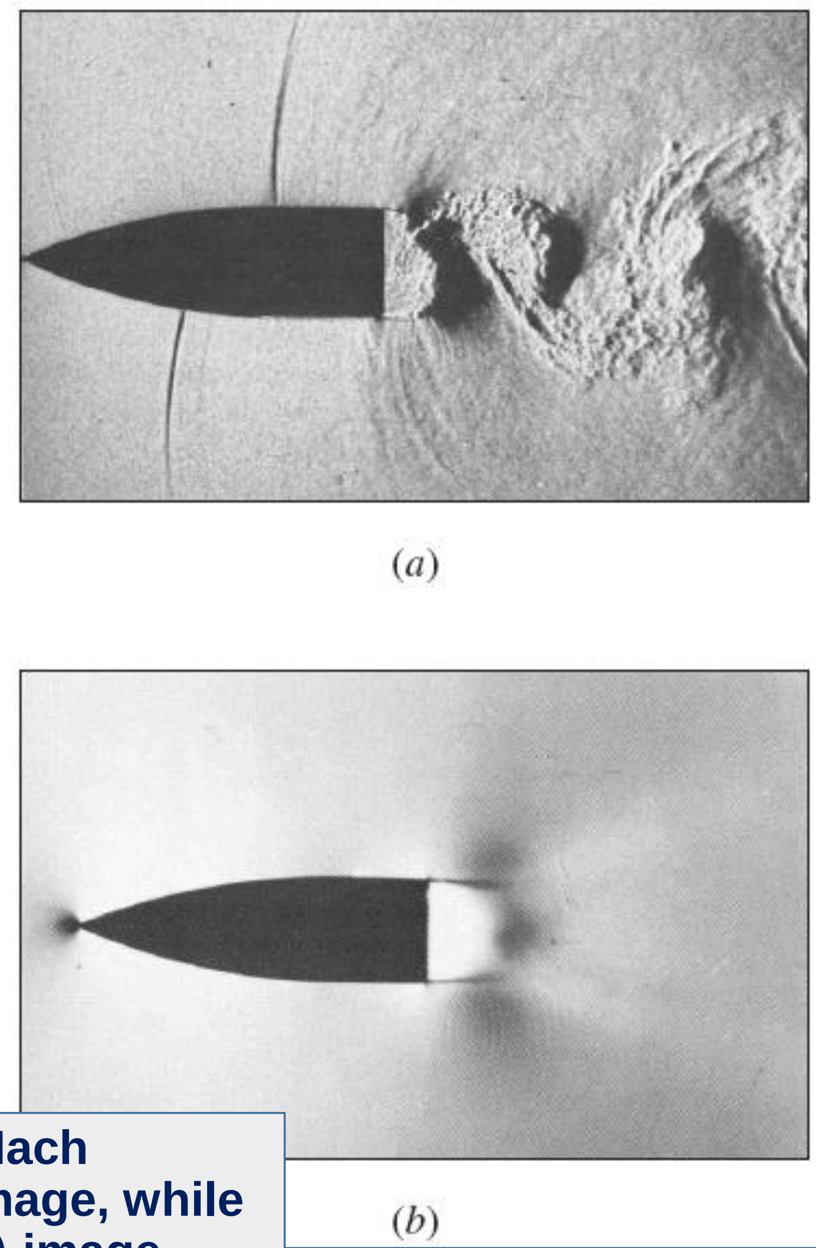
Natural flow: Fluid motion is due to natural means such as the buoyancy effect, which manifests itself as the rise of warmer (and thus lighter) fluid and the fall of cooler (and thus denser) fluid.



In this schlieren image of a girl in a swimming suit, the rise of lighter, warmer air adjacent to her body indicates that humans and warm-blooded animals are surrounded by thermal plumes of rising warm air.

Steady versus Unsteady Flow

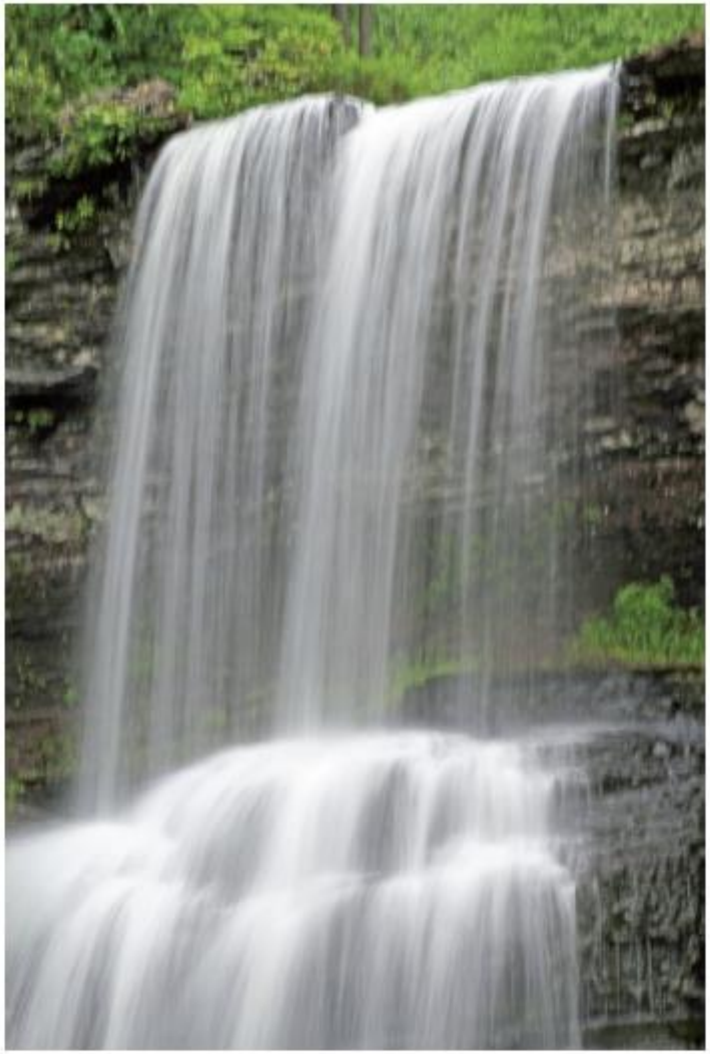
- **The term steady implies *no change at a point with time*.**
- **The opposite of steady is unsteady.**
- **The term uniform implies *no change with location* over a specified region.**
- **The term periodic refers to the kind of unsteady flow in which the flow oscillates about a steady mean.**
- **Many devices such as turbines, compressors, boilers, condensers, and heat exchangers operate for long periods of time under the same conditions, and they are classified as steady-flow devices.**



Oscillating wake of a blunt-based airfoil at Mach number 0.6. Photo (*a*) is an instantaneous image, while photo (*b*) is a long-exposure (time-averaged) image.

Steady versus Unsteady Flow-1

(*a*)

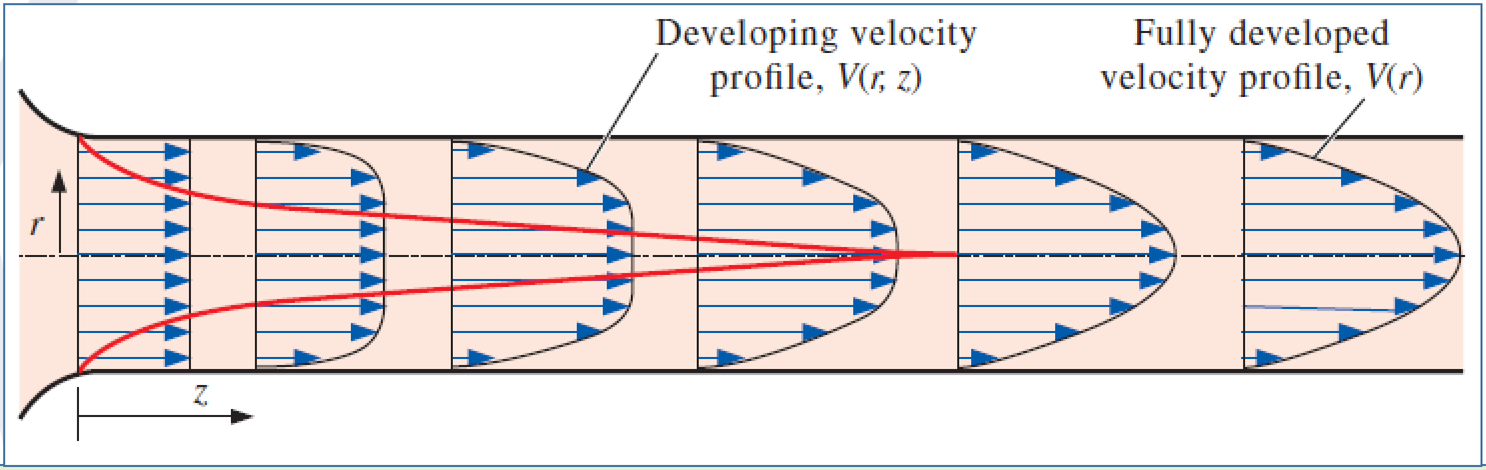


(*b*)

Comparison of (*a) instantaneous* snapshot of an unsteady flow, and (*b) long exposure picture of the same flow.*

One-, Two-, and Three-Dimensional Flows

- **A flow field is best characterized by its velocity distribution.**
- **A flow is said to be one-, two-, or three-dimensional if the flow velocity varies in one, two, or three dimensions, respectively.**
- **However, the variation of velocity in certain directions can be small relative to the variation in other**



The development of the velocity profile in a circular pipe. $V = V(r, z)$ and thus the flow is two-dimensional in the entrance region, and becomes one-dimensional downstream when the velocity profile fully develops and remains unchanged in the flow direction, $V = V(r)$.

10-3 VAPOR PRESSURE AND CAVITATION

- Saturation temperature T_{sat}: The temperature at which a pure substance changes phase at a given pressure.
- Saturation pressure P_{sat}: The pressure at which a pure substance changes phase at a given temperature.
- Vapor pressure (P_v): The pressure exerted by its vapor in phase equilibrium with its liquid at a given temperature. It is identical to the saturation pressure P_{sat} of the liquid ($P_v = P_{sat}$).

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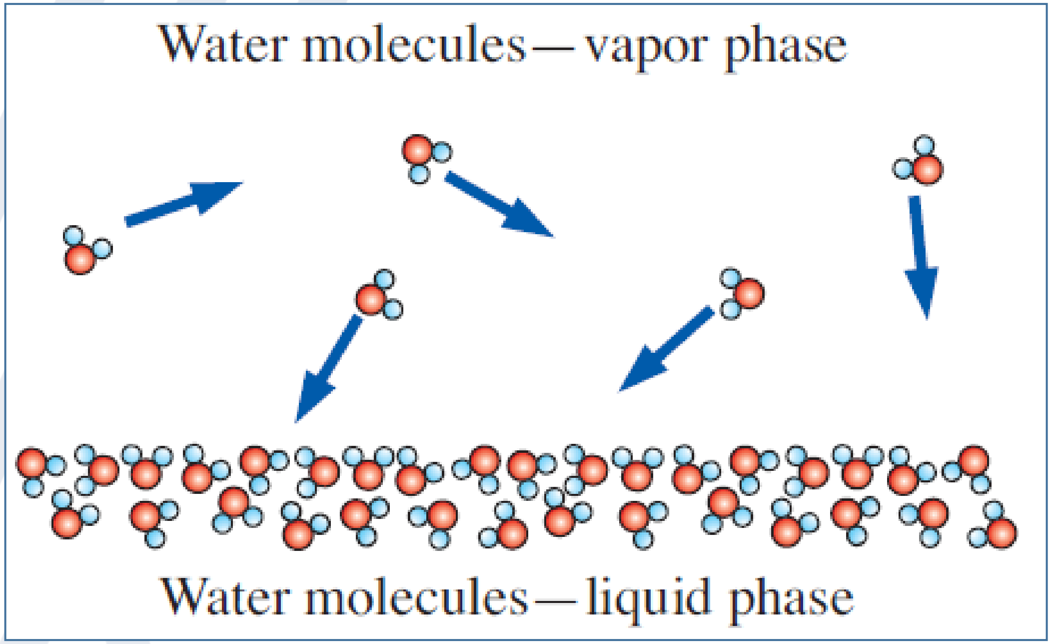
10-3 VAPOR PRESSURE AND CAVITATION

- Partial pressure: The pressure of a gas or vapor in a mixture with other gases. For example, atmospheric air is a mixture of dry air and water vapor, and atmospheric pressure is the sum of the partial pressure of dry air and the partial pressure of water vapor.

10-3 VAPOR PRESSURE AND CAVITATION-1



The vapor pressure (saturation pressure) of a pure substance (e.g., water) is the pressure exerted by its vapor molecules when the system is in phase equilibrium with its liquid molecules at a given temperature.

Saturation (or vapor) pressure of water at various temperatures

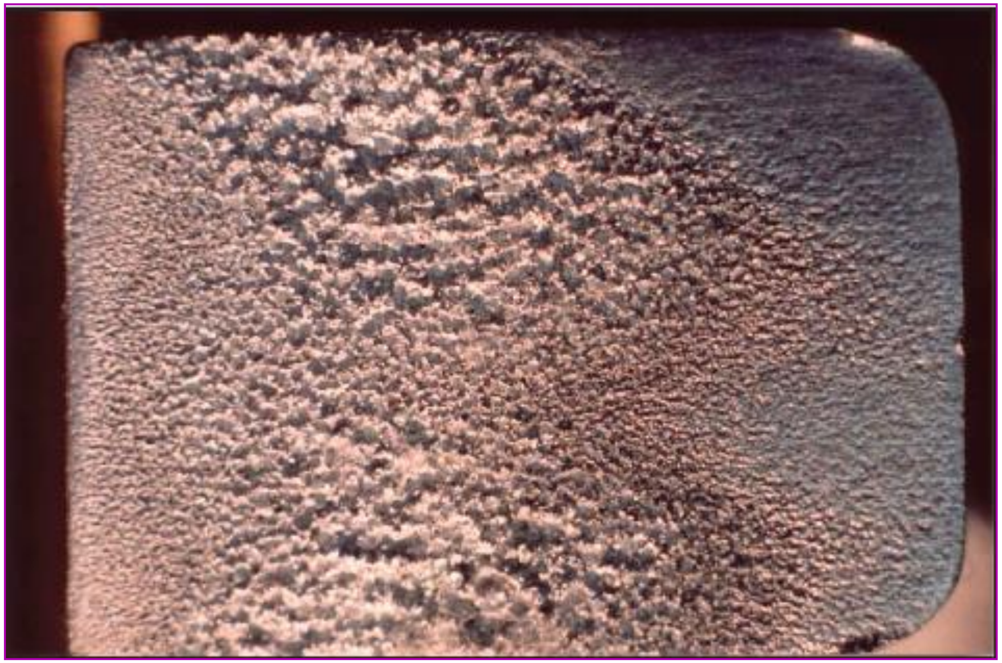
Temperature T, °C	Saturation Pressure P_{sat}, kPa
-10	0.260
-5	0.403
0	0.611
5	0.872
10	1.23
15	1.71
20	2.34
25	3.17
30	4.25
40	7.38
50	12.35
100	101.3(1 atm)
150	475.8
200	1554
250	3973
300	8581

10-3 VAPOR PRESSURE AND CAVITATION-2

- There is a possibility of the liquid pressure in liquid-flow systems dropping below the vapor pressure at some locations, and the resulting unplanned vaporization.

- The vapor bubbles (called cavitation bubbles since they form "cavities" in the liquid) collapse as they are swept away from the low-pressure regions, generating highly destructive, extremely high-pressure waves.

- This phenomenon, which is a common cause for drop in performance and even the erosion of impeller blades, is called cavitation, and it is an important consideration in the design of hydraulic turbines and pumps.

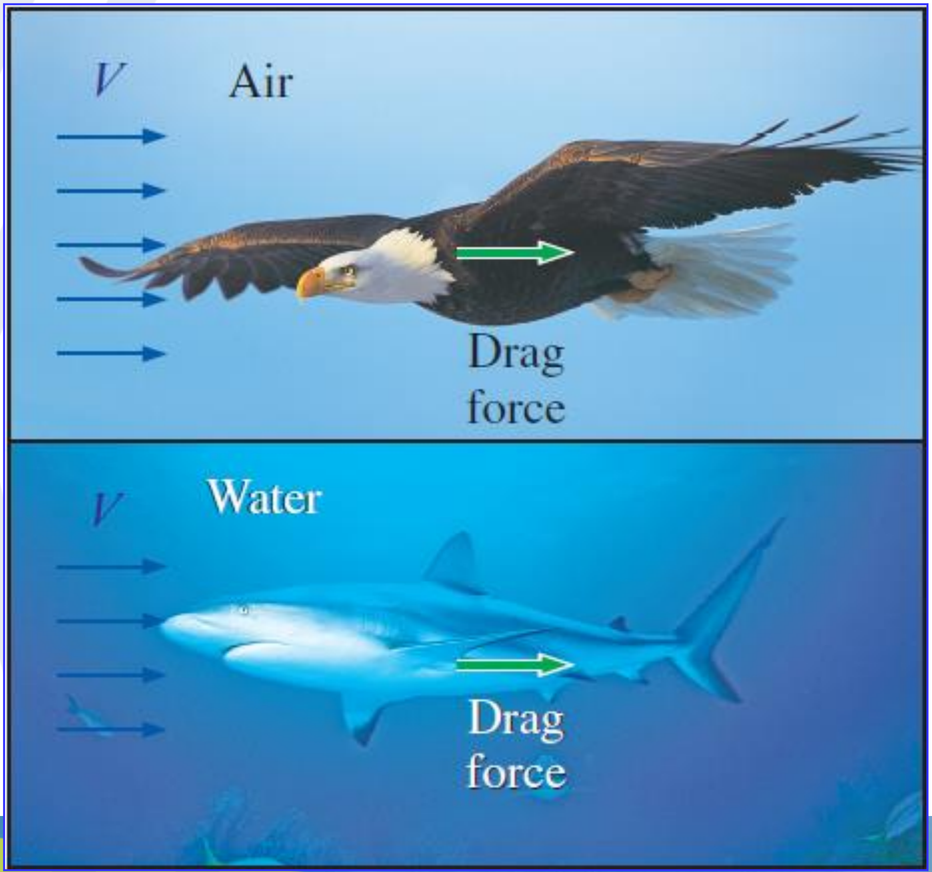


Cavitation damage on a 16-mm by 23-mm aluminum sample tested at 60 m/s for 2.5 h. The sample was located at the cavity collapse region downstream of a cavity generator specifically designed to produce high damage potential.

10-4 VISCOSITY

Viscosity: **A property that represents the internal resistance of a fluid to motion or the "fluidity".**

Drag force: **The force a flowing fluid exerts on a body in the flow direction. The magnitude of this force depends, in part, on viscosity**

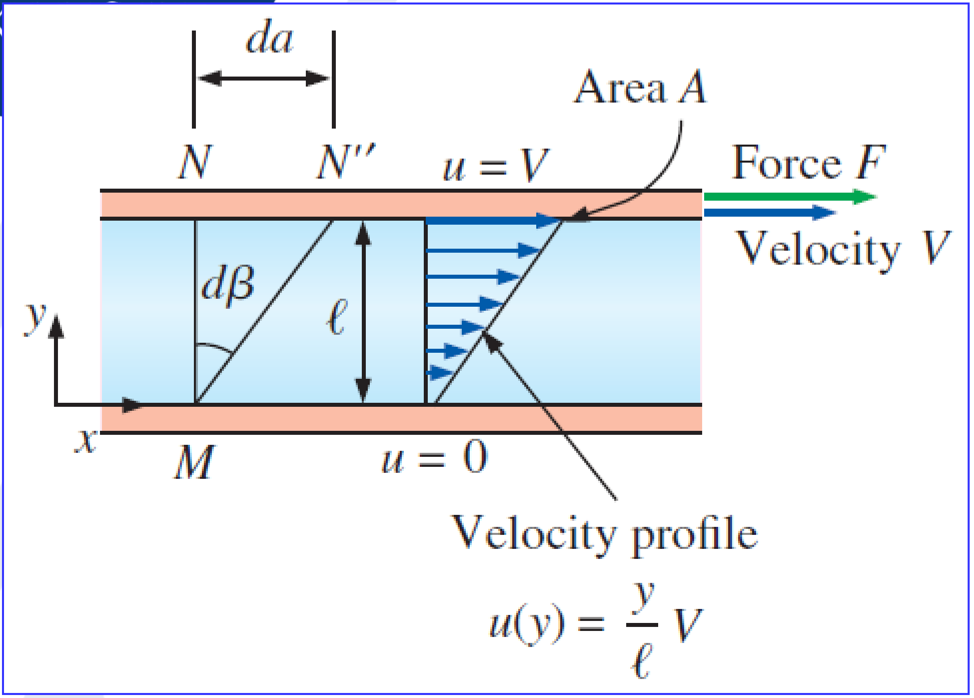


The viscosity of a fluid is a measure of its "*resistance to deformation*."

Viscosity is due to the internal frictional force that develops between different layers of fluids as they are forced to move relative to each other.

A fluid moving relative to a body exerts a drag force on the body, partly because of friction caused by viscosity.

10-4 VISCOSITY-1



Newtonian fluids: Fluids for which the rate of deformation is proportional to the shear stress.

$$\tau \propto \frac{d(d\beta)}{dt} \quad \textbf{or} \quad \tau \propto \frac{du}{dy}$$

$$\tau = \mu \frac{du}{dy} \qquad (\mathrm{N/m^2})$$

Shear stress

Shear force

$$F = \tau A = \mu A \frac{du}{dy} \qquad (\mathrm{N})$$

The behavior of a fluid in laminar flow between two parallel plates when the upper plate moves with a constant velocity.

$$\tau = \frac{F}{A} \qquad u(y) = \frac{y}{\ell} V \quad \textbf{and} \quad \frac{du}{dy} = \frac{V}{\ell}$$

$$d\beta \approx \tan d\beta = \frac{da}{\ell} = \frac{V\,dt}{\ell} = \frac{du}{dy} dt \qquad \frac{d\beta}{dt} = \frac{du}{dy}$$

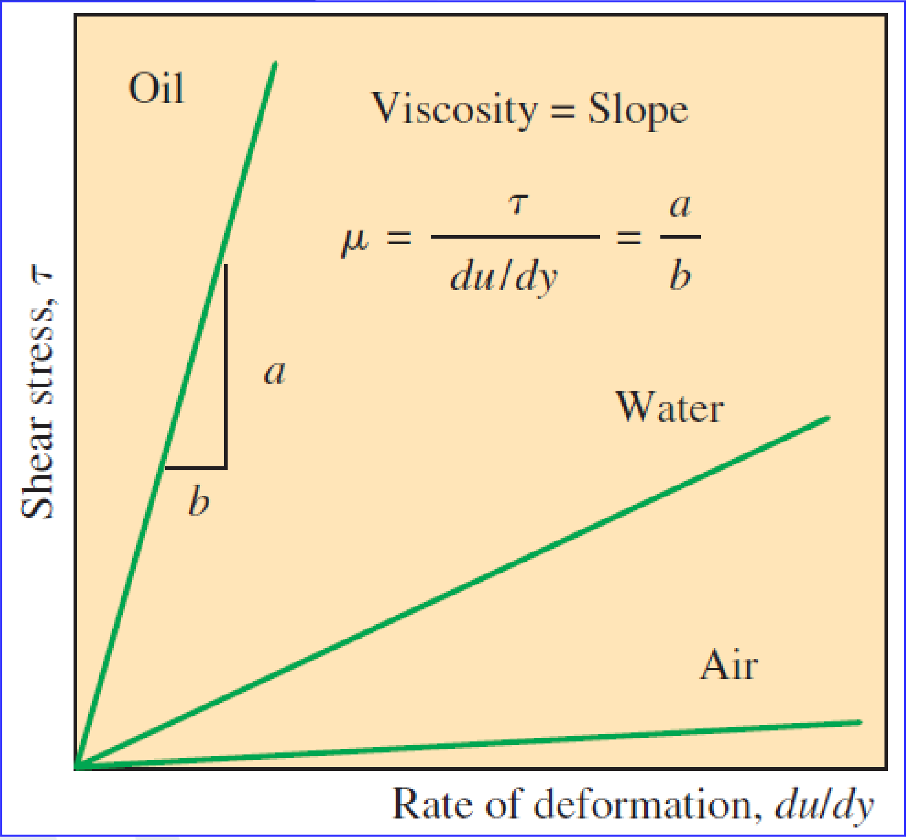
μ coefficient of viscosity

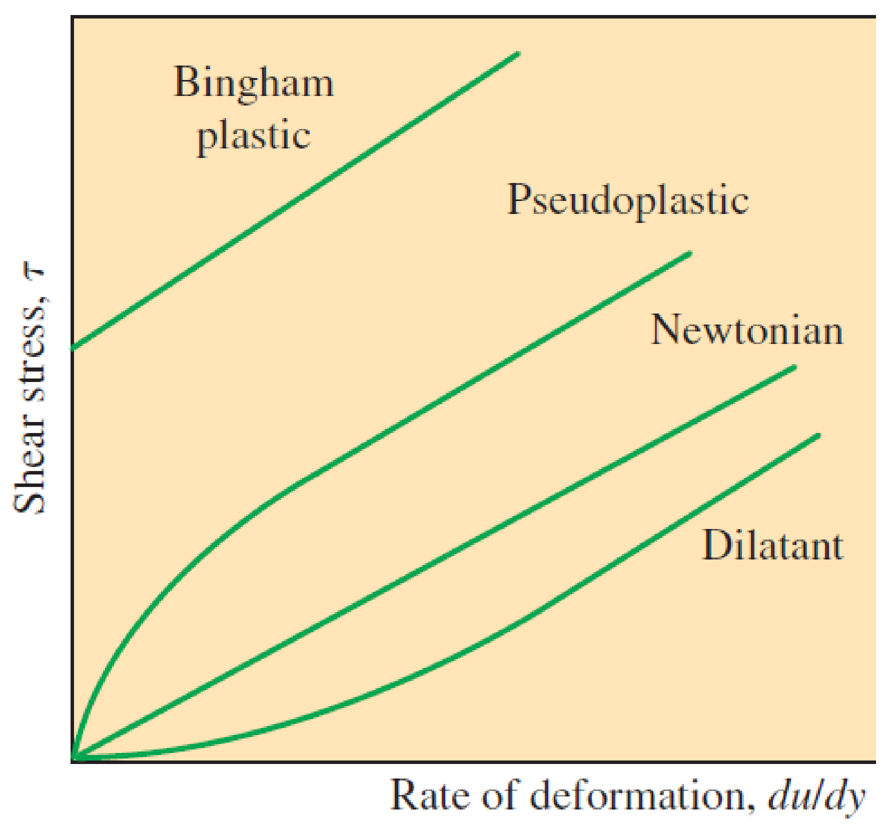
Dynamic (absolute) viscosity

$\mathrm{kg/m \cdot s}$ or $\mathrm{N \cdot s/m^2}$ or $\mathrm{Pa \cdot s}$

$1 \text{ poise} = 0.1\ \mathrm{Pa \cdot s}$

VISCOSITY-2





The rate of deformation (velocity gradient) of a Newtonian fluid is proportional to shear stress, and the constant of proportionality is the viscosity.

Variation of shear stress with the rate of deformation for Newtonian and non-Newtonian fluids (the slope of a curve at a point is the apparent viscosity of the fluid at that point).

A Newtonian fluid is defined as one with constant viscosity, with zero shear rate at zero shear stress, that is, the shear rate is directly proportional to the shear stress.

A **non-Newtonian fluid** is a fluid that does not follow Newton's law of viscosity, i.e., constant viscosity independent of stress. In non-Newtonian fluids, viscosity can change when under force to either more liquid or more solid. Ketchup, for example, becomes runnier when shaken and is thus a non-Newtonian fluid.

A Newtonian fluid's viscosity remains constant, no matter the amount of shear applied for a constant temperature.. These fluids have a linear relationship between viscosity and shear stress.

Examples:

- Water
- Mineral oil
- Gasoline
- Alcohol

Kinematic viscosity

VISCOSITY-3

$$v = \mu/\rho$$

$\mathrm{m^2/s}$ **or stoke**

1 stoke = 1 $\mathrm{cm^2/s}$

For *liquids*, both the dynamic and kinematic viscosities are practically independent of pressure, and any small variation with pressure is usually disregarded, except at extremely high pressures.

For *gases*, this is also the case for dynamic viscosity (at low to moderate pressures), but not for kinematic viscosity since the density of a gas is proportional to its pressure.

where T is absolute temperature and a and b are experimentally determined constants. Note that measuring viscosity at two different temperatures is sufficient to determine these constants. For air at atmospheric conditions, the values of these constants are a=5 1.458 3 1026 kg/(m?s?K1/2) and b = 5 110.4 K. The

$$\mu = \frac{aT^{1/2}}{1 + b/T}$$

For gases

$$\mu = a10^{b/(T-c)}$$

For liquids

VISCOSITY-3

Kinematic viscosity

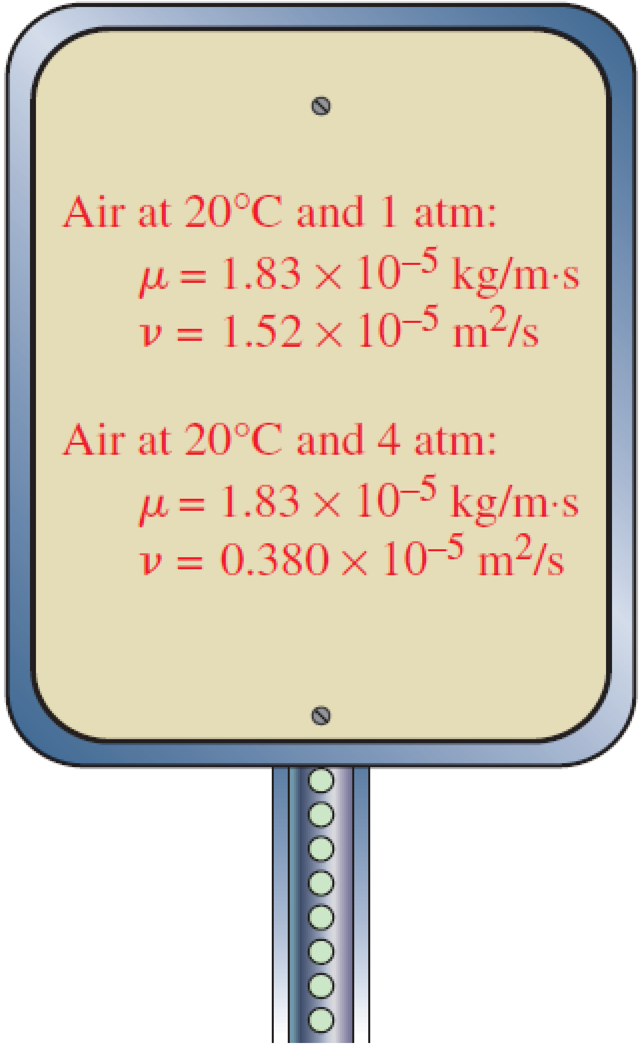
$\nu = \mu/\rho$

m^2/s **or stoke**

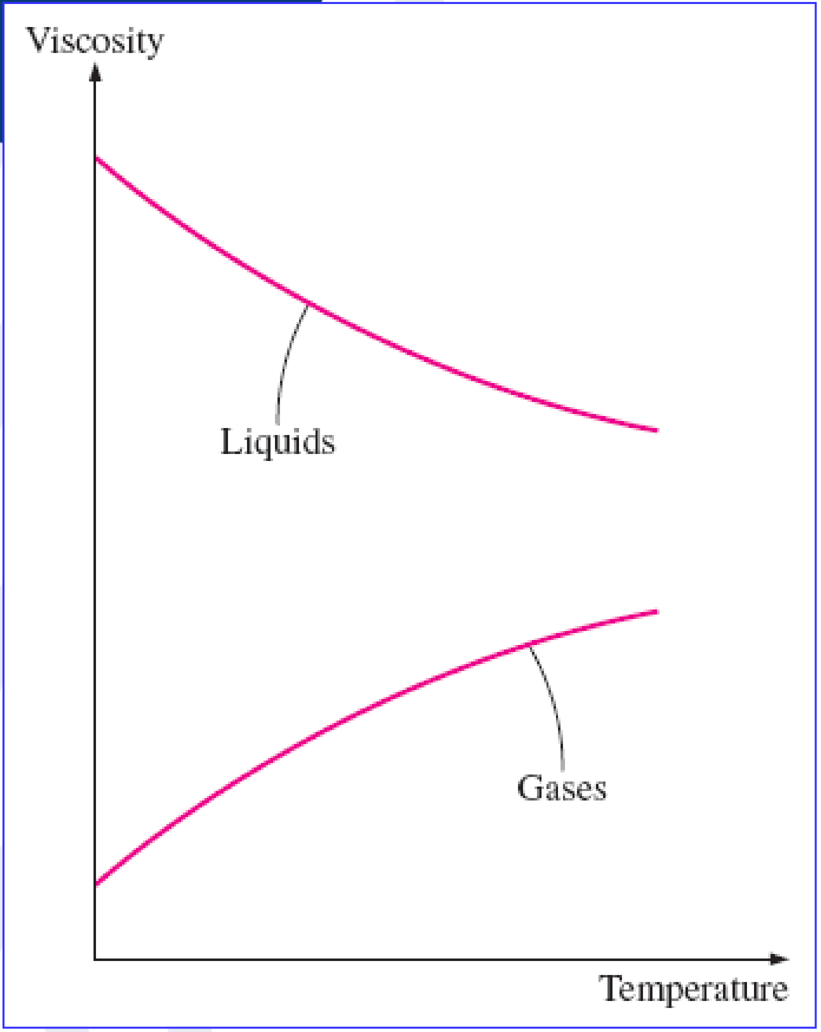
1 stoke = 1 cm^2/s

dynamic viscosity is a measure of force, while **kinematic viscosity** is a measure of velocity.

Dynamic viscosity, in general, does not depend on pressure, but kinematic viscosity does.



10-4 VISCOSITY-4

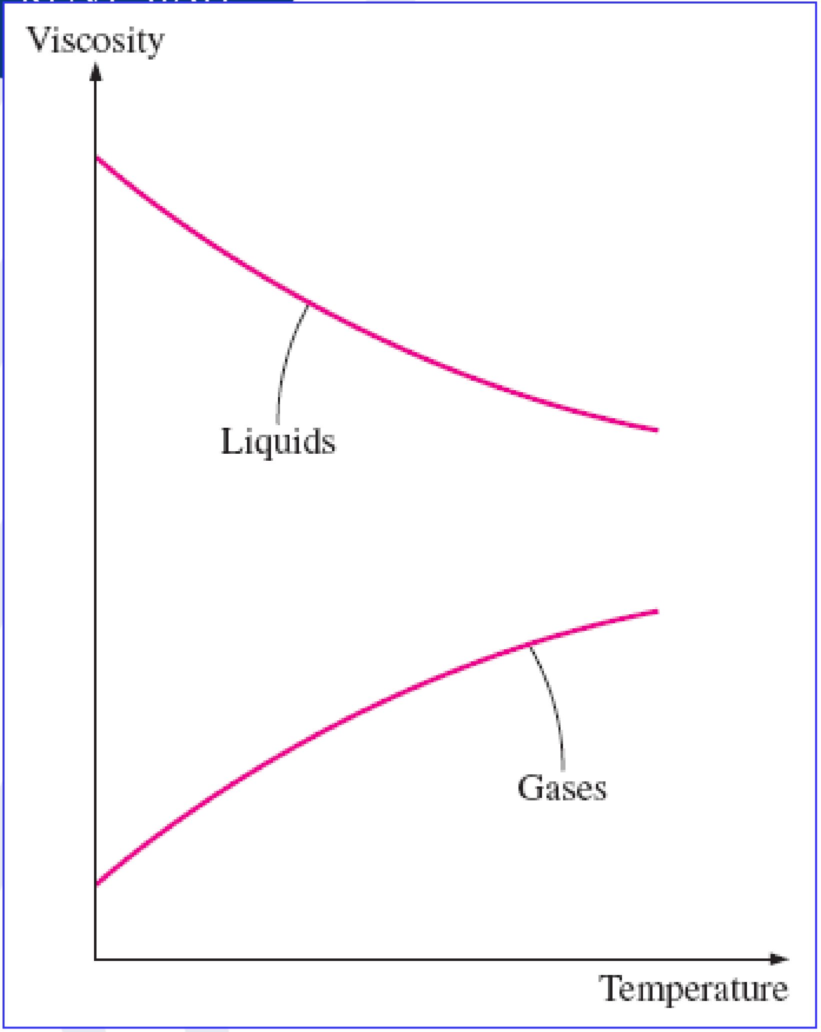


The viscosity of liquids decreases, and the viscosity of gases increases with temperature.

The viscosity of a fluid is directly related to the pumping power needed to transport a fluid in a pipe or to move a body through a fluid.

Viscosity is caused by the cohesive forces between the molecules in liquids and by the molecular collisions in gases, and it varies greatly with temperature.

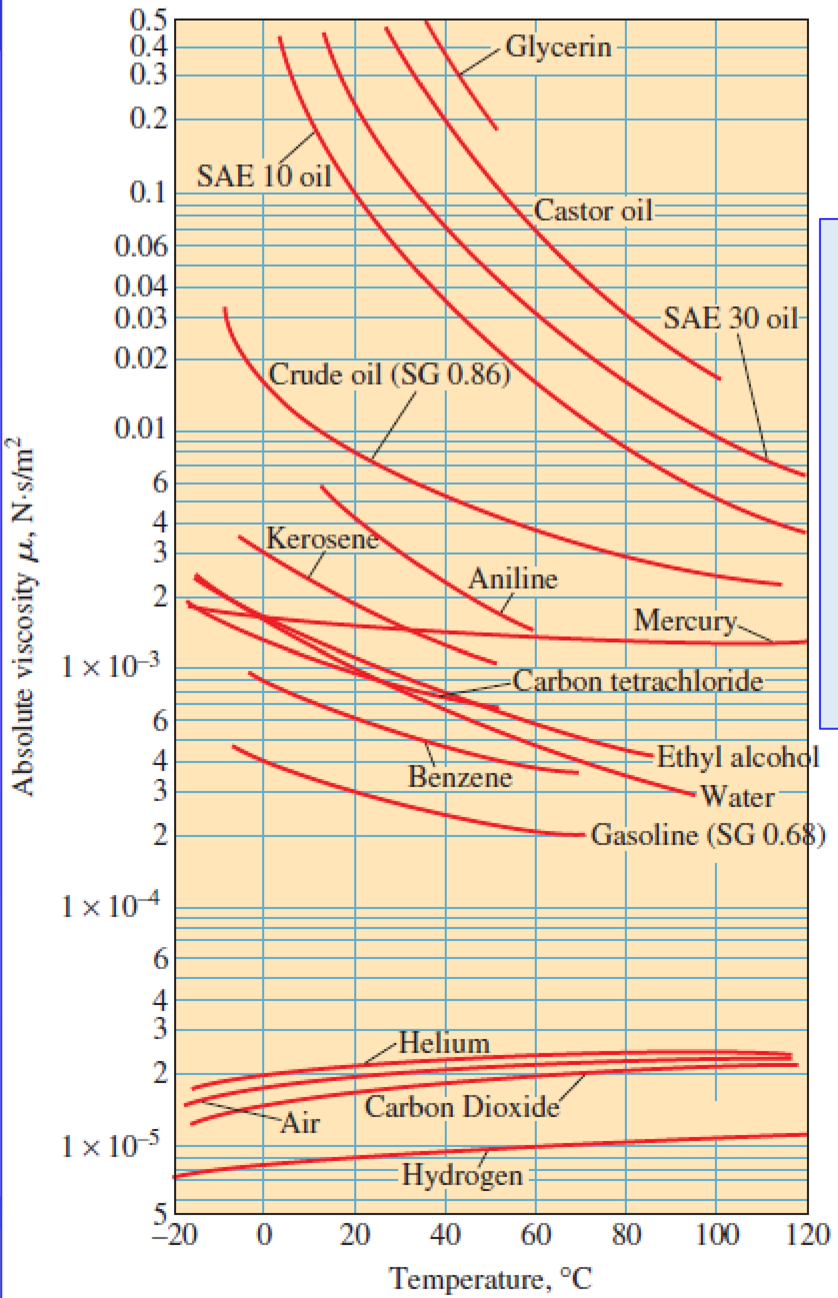
10-4 VISCOSITY-4



- **In a liquid,** the molecules possess more energy at higher temperatures, and they can oppose the large cohesive intermolecular forces more strongly. As a result, the energized liquid molecules can move more freely.
- **In a gas,** the intermolecular forces are negligible, and the gas molecules at high temperatures move randomly at higher velocities. This results in more molecular collisions per unit volume per unit time and therefore in greater resistance to flow.

The viscosity of liquids decreases and the viscosity of gases increases with temperature.

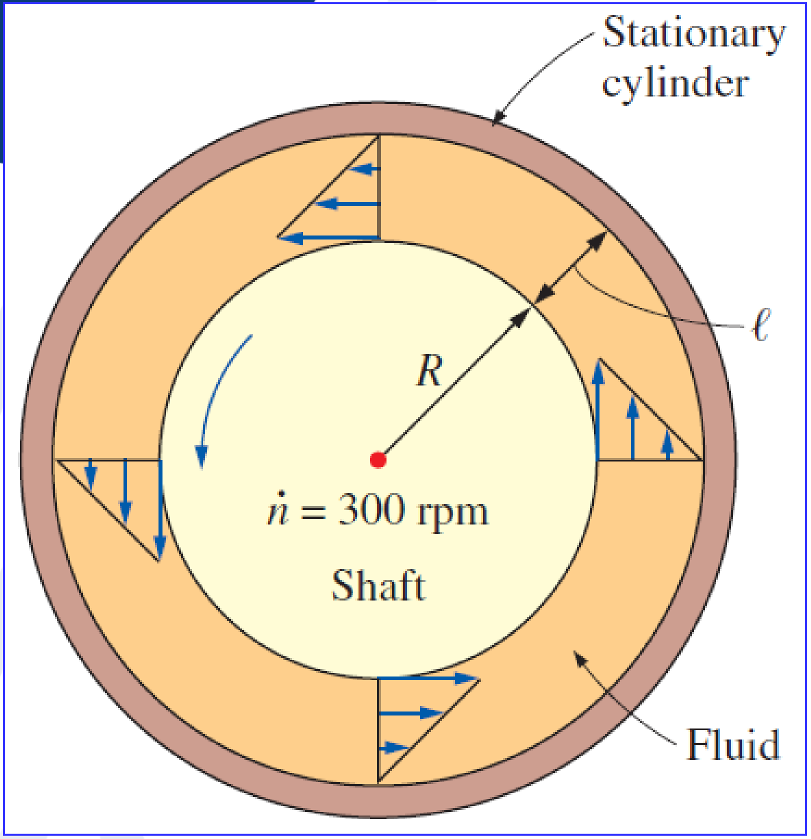
10-4 Viscosity-5



The variation of dynamic (absolute) viscosity of common fluids with temperature at 1 atm
(1 $N.s/m^2$ = 1 kg/m·s = 0.020886 lbf·s/ft^2)

Dynamic viscosity of some fluids at 1 atm and 20°C (unless otherwise stated)

Fluid	Dynamic Viscosity μ, kg/m · s
Glycerin:	
−20°C	134.0
0°C	10.5
20°C	1.52
40°C	0.31
Engine oil:	
SAE 10W	0.10
SAE 10W30	0.17
SAE 30	0.29
SAE 50	0.86
Mercury	0.0015
Ethyl alcohol	0.0012
Water	
0°C	0.0018
20°C	0.0010
100°C (liquid)	0.00028
0°C (vapor)	0.000012
Blood, 37°C	0.00040
Gasoline	0.00029
Ammonia	0.00015
Air	0.000018
Hydrogen, 0°C	0.0000088



10-4 VISCOSITY-6

L	**length of the cylinder**
$\dot{n}$	**number of revolutions per unit time**

$$\mathrm{T} = FR = \mu \frac{2\pi R^3 \omega L}{\ell} = \mu \frac{4\pi^2 R^3 \dot{n} L}{\ell}$$

This equation can be used to calculate the viscosity of a fluid by measuring torque at a specified angular velocity.

Therefore, two concentric cylinders can be used as a *viscometer*, a device that measures viscosity.

EXAMPLE 10–3 Determining the Viscosity of a Fluid

The viscosity of a fluid is to be measured by a viscometer constructed of two 40-cm-long concentric cylinders (**Fig. 10–23**). The outer diameter of the inner cylinder is 12 cm, and the gap between the two cylinders is 0.15 cm. The inner cylinder is rotated at 300 rpm, and the torque is measured to be 1.8 N·m. Determine the viscosity of the fluid.

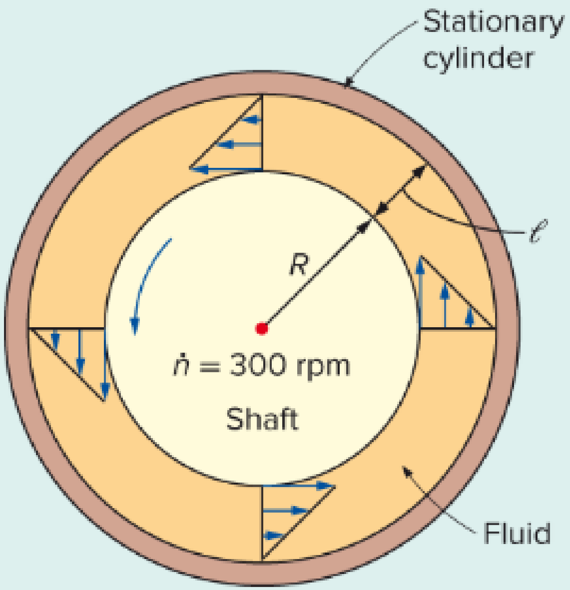


FIGURE 10–23
Schematic for **Example 10–3** (not to scale).

SOLUTION

The torque and the rpm of a double cylinder viscometer are given. The viscosity of the fluid is to be determined.

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Assumptions

1 The inner cylinder is completely submerged in the fluid. **2** The viscous effects on the two ends of the inner cylinder are negligible.

Analysis

The velocity profile is linear only when the curvature effects are negligible, and the profile can be approximated as being linear in this case since $\ell/R = 0.025 \ll 1$. Solving **Eq. 10–11** for viscosity and substituting the given values, the viscosity of the fluid is determined to be

$$\mu = \frac{T\ell}{4\pi^2 R^3 \dot{n} L} = \frac{(1.8\ \text{N}\cdot\text{m})(0.0015\ \text{m})}{4\pi^2 (0.06\ \text{m})^3 \left(300\ \dfrac{1}{\text{min}}\right)\left(\dfrac{1\ \text{min}}{60\ \text{s}}\right)(0.4\ \text{m})} = \mathbf{0.158\ N\cdot s/m^2}$$

Discussion

Viscosity is a strong function of temperature, and a viscosity value without a corresponding temperature is of little usefulness. Therefore, the temperature of the fluid should have also been measured during this experiment, and reported with this calculation.

10-5 Surface Tension And Capillary Effect

- Liquid droplets behave like small balloons filled with the liquid on a solid surface, and the surface of the liquid acts like a stretched elastic membrane under tension.
- The pulling force that causes this tension to acts parallel to the surface and is due to the attractive forces between the molecules of the liquid.
- The magnitude of this force per unit length is called surface tension (or *coefficient of surface tension*) and is usually expressed in the unit N/m.
- This effect is also called *surface energy* [per unit area] and is expressed in the equivalent unit of N · m/m^2.

10-5 Surface Tension And Capillary Effect

Some consequences of surface tension:

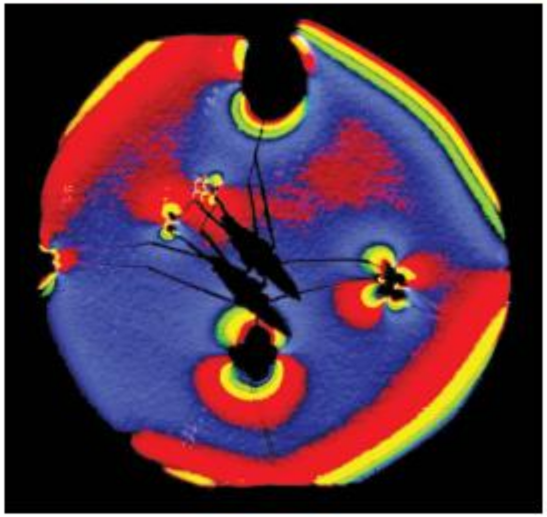
(a) drops of water beading up on a leaf,

(b) *(b) a water strider sitting on top of the* surface of water,

(c) a color schlieren image of the water strider revealing how the water surface dips down where its feet contact the water (it looks like two insects but the second one is just a shadow).

(a)

(b)



(c)

Capillary Effect

Capillary effect: The rise or fall of a liquid in a small-diameter tube inserted into the liquid.

Capillaries: Such narrow tubes or confined flow channels.

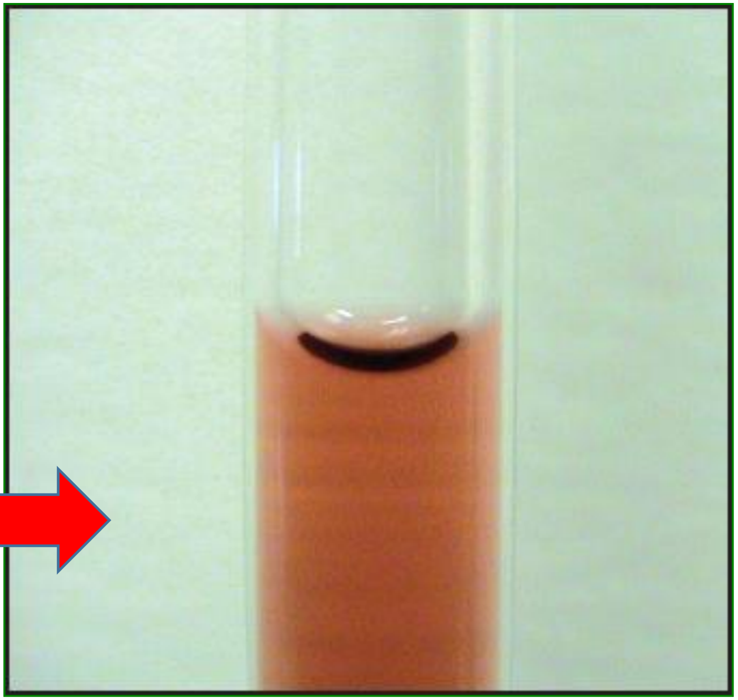
The capillary effect is partially responsible for the rise of water to the top of tall trees.

Meniscus: The curved free surface of a liquid in a capillary tube.

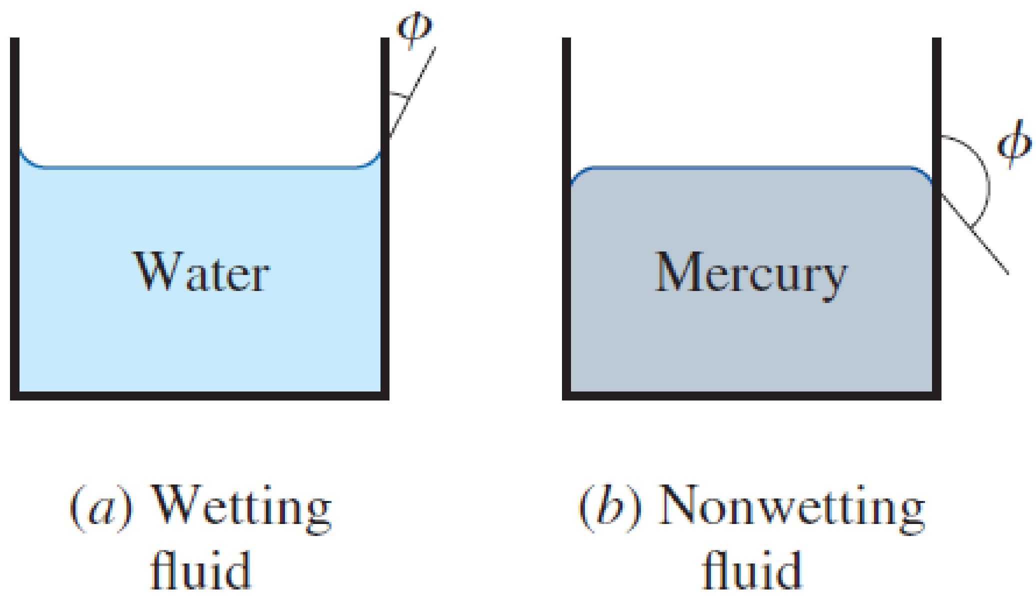
The strength of the capillary effect is quantified by the contact (or *wetting*) angle, defined as *the angle that the tangent to the liquid surface makes with the solid surface at the point of contact*.

Capillary Effect

The meniscus of colored water in a 4-mm-inner-diameter glass tube. Note that the edge of the meniscus meets the wall of the capillary tube at a very small contact angle.



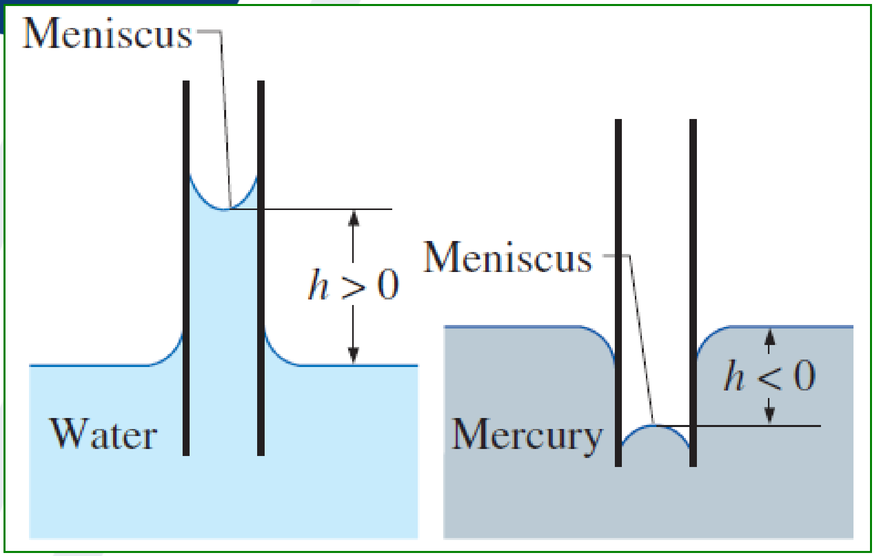
Capillary Effect

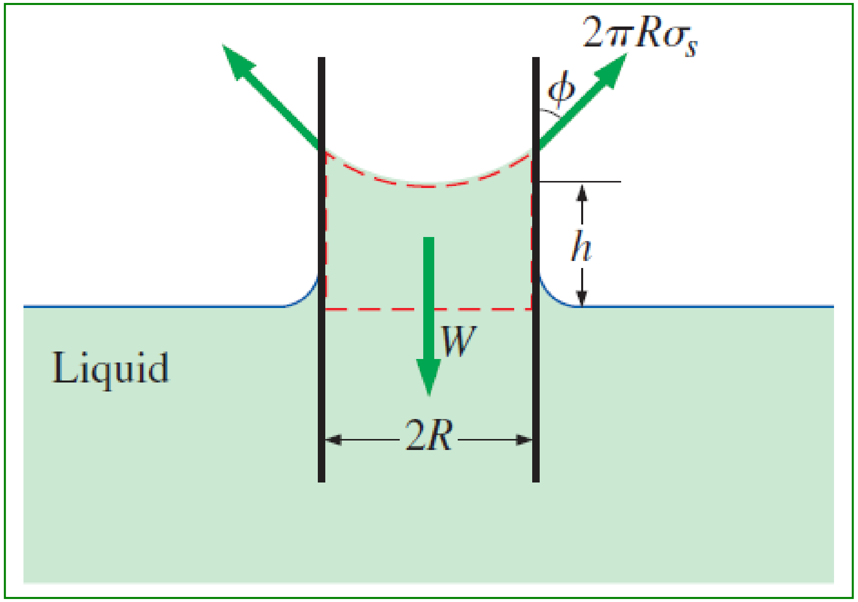


The contact angle for wetting and nonwetting fluids.

A wetting liquid is a liquid that forms a contact angle with the solid which is smaller then 90°. A non-wetting liquid creates a **contact angle between 90° and 180° with the solid**.

Capillary Effect-1





The capillary rise of water and the capillary fall of mercury in a small-diameter glass tube.

The forces acting on a liquid column that has risen in a tube due to the capillary effect.

$$\textit{Capillary rise:} \qquad h = \frac{2\sigma_s}{\rho g R}\cos\phi \quad (R = \text{constant})$$

- **Capillary rise is inversely proportional to the radius of the tube and density of the liquid.**

- Note that the capillary rise is inversely proportional to the radius of the tube. Therefore, the thinner the tube is, the greater the rise (or fall) of the liquid in the tube.
- In practice, the capillary effect for water is usually negligible in tubes whose diameter is greater than 1 cm.
- When pressure measurements are made using manometers and barometers, it is important to use sufficiently large tubes to minimize the capillary effect.
- The capillary rise is also inversely proportional to the density of the liquid, as expected.
- Therefore, in general, lighter liquids experience greater capillary rises. Finally, it should be kept in mind that **Eq. 10–15** is derived for constant-diameter tubes and should not be used for tubes of variable cross

Capillary rise: $$h = \frac{2\sigma_s}{\rho g R}\cos\phi \quad (R = \text{constant}) \qquad (10\text{–}15)$$

EXAMPLE 10–4 The Capillary Rise of Water in a Tube

A 0.6-mm-diameter glass tube is inserted into water at 20°C in a cup. Determine the capillary rise of water in the tube (**Fig. 10–32**).

the contact angle of water (and
most other organic liquids)
with glass is nearly zero

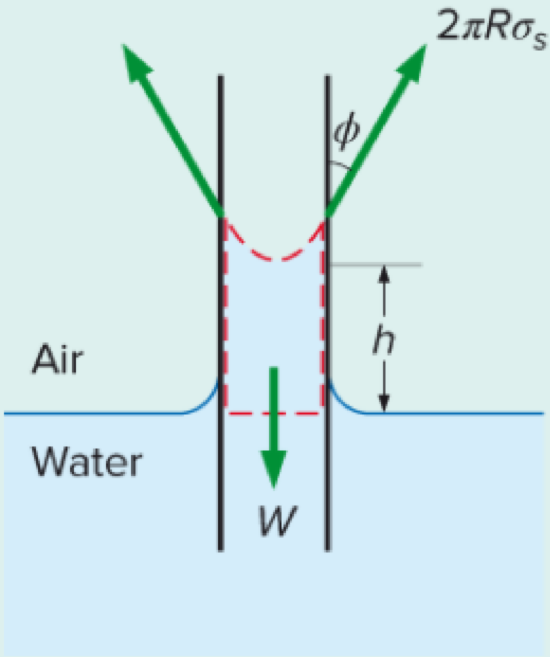


FIGURE 10–32
Schematic for **Example 10–4**.

SOLUTION

The rise of water in a slender tube as a result of the capillary effect is to be determined.

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Assumptions

1 There are no impurities in the water and no contamination on the surfaces of the glass tube. **2** The experiment is conducted in atmospheric air.

Properties

The surface tension of water at 20°C is 0.073 N/m (**Table 10–3**). The contact angle of water with glass is approximately 0° (from preceding text). We take the density of liquid water to be 1000 kg/m^3.

Analysis

The capillary rise is determined directly from **Eq. 10–15** by substituting the given values, yielding

$$h = \frac{2\sigma_s}{\rho g R}\cos\phi = \frac{2(0.073\ \text{N/m})}{(1000\ \text{kg/m}^3)(9.81\ \text{m/s}^2)(0.3\times 10^{-3}\text{m})}(\cos 0^\circ)\left(\frac{1\ \text{kg}\cdot\text{m/s}^2}{1\ \text{N}}\right)$$

$$= 0.050\ \text{m} = \mathbf{5.0\ cm}$$

Therefore, water rises in the tube 5 cm above the liquid level in the cup.

Summary

- **The No-Slip Condition**
- **Classification of Fluid Flows**
  - Viscous versus Inviscid Regions of Flow
  - Internal versus External Flow
  - Compressible versus Incompressible Flow
  - Laminar versus Turbulent Flow
  - Natural (or Unforced) versus Forced Flow
  - Steady versus Unsteady Flow
  - One-, Two-, and Three-Dimensional Flows
- **Viscosity**
- **Surface Tension and Capillary Effect**